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The health and future of coral reef systems

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Abstract

Coral reefs are among the most productive and diverse ecosystems on earth and provide a multitude of valuable ecosystem services. Moreover, the resources derived from coral reefs are essential to the food security of millions of people living within tropical coastal communities. Unfortunately, burgeoning human populations in coastal regions are placing an unsustainable burden on these resources such that degradation of coral reefs is common. In addition, during 1998, El Niño driven increases in sea temperature caused a mass bleaching event that further degraded many of the world's coral reefs. This article provides a brief review of the status of the world's coral reefs and highlights their value to society. Also, the anthropogenic and natural disturbances that threaten the future of coral reefs are discussed and finally, this article offers some potential remedies that promote sustainable use of coral reef resources thus ensuring their future survival.

1. Introduction

Coral reefs are the most diverse of all marine ecosystems and support a myriad of fish and invertebrate species [1]. The fundamental unit of these ecosystems is the scleractinian (hard or reef-building) coral itself. Most corals are colonial organisms consisting of thousands of individual polyps. In order to survive, corals, like all organisms, have a specific set of physiological and environmental requirements. Corals flourish only in clear, shallow, warm water that ranges between 18 and 30°C [2]. Subsequently, coral reefs are limited to the tropics with most major reef systems occurring between the Tropic of Cancer and the Tropic of Capricorn. Light is also essential for the survival of reef-building corals and, as a consequence, their distribution is limited to depths shallower than 100 m [3]. Corals also are fairly intolerant to fluctuations in salinity generally preferring salinities that range between 32 and 40‰ [3].

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Modern coral reefs have been present in the world's oceans in, more or less, their current form since the Mesozoic era some 250 million yr ago [4]. Coral reefs are unique among marine ecosystems because they flourish in waters that are virtually devoid of nutrients [3,5]. Their high productivity has prompted The World Conservation Strategy (IUCN/UNEP/WWF) to recognise coral reefs as one of the essential global life support systems necessary for food production, health and other aspects of human survival and sustainable development [6].

Bleaching and subsequent mortality of corals as a result of increased sea temperatures is a relatively recent phenomenon that has resulted in a dramatic decline in the number of healthy reefs around the world [4,7]. However, long before climate change became a major problem for coral reefs, burgeoning human populations, especially in coastal areas, and increasing prevalence of non-sustainable, exploitive activities have been degrading coral reefs throughout the world [1,7–13]. Indeed, as early as the 1930s Gardiner [14] expressed concern regarding the apparent decline in species numbers on reefs he studied close to population centres in the Indian Ocean. Recently, Jameson et al. [9] reported that reefs in 93 countries had been damaged or destroyed and Wilkinson [8] stated that 10% of the world's reefs had already disappeared and it is predicted that within the next two decades an additional 20% might collapse [9]. Reefs in the Indian Ocean have already suffered heavier damage, IUCN/UNEP [15] estimating that already 20% have been lost or severely damaged. Malakoff [16] estimated that within the last few hundred year nearly 1200 extinctions had been recorded, most of which, he thought, were little known species inhabiting coral reefs. Reaka-Kudla [16] thought that this worrying trend of species extinction would only increase and predicted that within the next 40 yr 1.2 million species that depend on coral reefs would be extinct. If neglect of ecosystems such as coral reefs, and the life-support services they provide continues unabated then it "could ultimately compromise the sustainability of humans in the biosphere" [17, p. 253].

2. Value of coral reefs

The value of the biosphere (collective term encompassing all regions of the globe that support life) and the services it provides has been recently estimated at between \$16 trillion and \$54 trillion (10^{12}) USD annually [17] which is between 1 and 3 times the gross national product (GNP) of the entire globe. Marine ecosystems alone contributed 63% of this value and coral reefs, in particular, contributed 1.8% (\$375 billion USD) [17]. As coral reefs constitute only 0.2% of the world's marine ecosystems [18] these figures demonstrate that the contribution of coral reefs to the welfare of the globe and the people living on it is disproportionately large. However, it should be noted that some activities conducted on coral reefs such as coral mining are destructive and, despite reaping short-term economic gains, have long-term costs associated with them.

2.1. Food resources

Coral reefs provide a diverse array of items such as fish, molluscs (clams, scallops, octopi, oysters), crustaceans (crabs, lobsters, shrimps), turtles (adults and eggs) and algae that are consumed by humans [6]. Coral reefs provide between 10 and 12% of the harvest of finned fish from tropical countries and up to 25% in developing nations [8,19]. These estimates should be considered as the lower end of the scale as many fish are caught by subsistence fisherman and are never recorded officially. In addition, 9 million metric tons of shellfish and molluscs are harvested from coral reefs annually [9]. Because many of the world's coral reefs bound the coastlines of developing countries they are essential for the survival of the people who reside within the coastal zones of these nations [1,7,12]. Indeed, the fish catches from shallow coastal waters (Fig. 1) dominated by coral reefs in Asia alone are estimated to support 1 billion people [9,20] and destruction of these reefs would undoubtedly lead to substantial reduction of the supply of animal protein in the diets of the populations of the coastal countries.

2.2. Tourism

Much of the economic value of coral reefs stems from their intrinsic beauty that attracts millions of tourists annually to gaze upon their magnificence. Indeed, in many parts of the world, especially in small island nations such as Maldives, Mauritius, Solomon's, Fiji, and those in the Caribbean, tourism is vital to their economies. In Seychelles tourism is the single largest foreign exchange earner [6] and in Florida nearby coral reefs contribute an estimated $1.6 billion USD to the local economy each year [21]. Tourism contributes 45% of the GNP of Maldives [7,22] and up to 50% of the GNP of some Caribbean countries. In 1990 tourism in the Caribbean generated $8.9 billion USD and employed 350 000 people [9].

Fig. 1. The vast majority of the human population of coastal communities in tropical developing nations are dependent on shallow water fisheries for the provision of animal protein. Many of the fish are dependent on coral reefs for part, or the whole, of their life cycle.

2.3. Coastal protection

Many of the world's coral reefs are situated along continental margins and surround small islands. As such, they perform an important role in protecting the shoreline from erosion by oceanic swells and tropical storms [1,3,7,9,23,24]. The protection offered by coral reefs permits productive mangrove and wetland habitats to flourish in sheltered areas and provide essential nursery areas for juvenile fish, many of which inhabit coral reefs as adults [1,3,9,24]. In addition, accretion of white, coral sand along coastlines protected by coral reefs is a significant attractant to thousands of tourists annually.

2.4. Biodiversity

Coral reefs are second only to tropical rainforests as the most diverse ecosystem in the world (Fig. 2a and b). Only one of the 33 phyla that exist on this planet does not occur on coral reefs and 15 occur nowhere else [25]. Recently, Reaka-Kudla [16] estimated that coral reefs support between 1 and 9 million species. Of these, only approximately 4000 species of fish and 800 species of coral have been described [16,26].

2.5. Medicines

The inhabitants of coral reefs are coming under increasing scrutiny from pharmaceutical companies in search of potential new drugs. The chronic overuse of traditional antibiotics such as penicillin has resulted in many bacteria, that were once killed by these drugs, becoming resistant. Subsequently, new sources of drugs to fight disease are being sought [18]. Because many inhabitants of coral reefs produce bioactive substances for their own defence against predators and competitors [27–32] and the environment [33] they are prime targets for this type of research. Indeed, half of all cancer research is concentrating on active compounds derived from marine organisms [34,35] and the calcium carbonate skeletons of corals are already being used for human bone grafts [21].

2.6. Biotechnology (alternative to medicines)

The field of marine biotechnology is an area which provides many exciting scientific and economic opportunities. Coral reef organisms are a reservoir for biomedically important substances, biodegraders, antifouling and anticorrosion substances, biosensors, biocatalysts, biopolymers and many other potentially important compounds and products [36]. Substances or naturally occurring metabolites of reef sponges, sea whips, and corals have been found to have antiviral, antifungal, antibacterial and anti-inflammatory properties [37–41]. In addition, reef organisms contain numerous compounds useful for a variety of other commercial applications, such as amino acids, vitamins, lipids, waxes, polysaccharides and pigments [42].

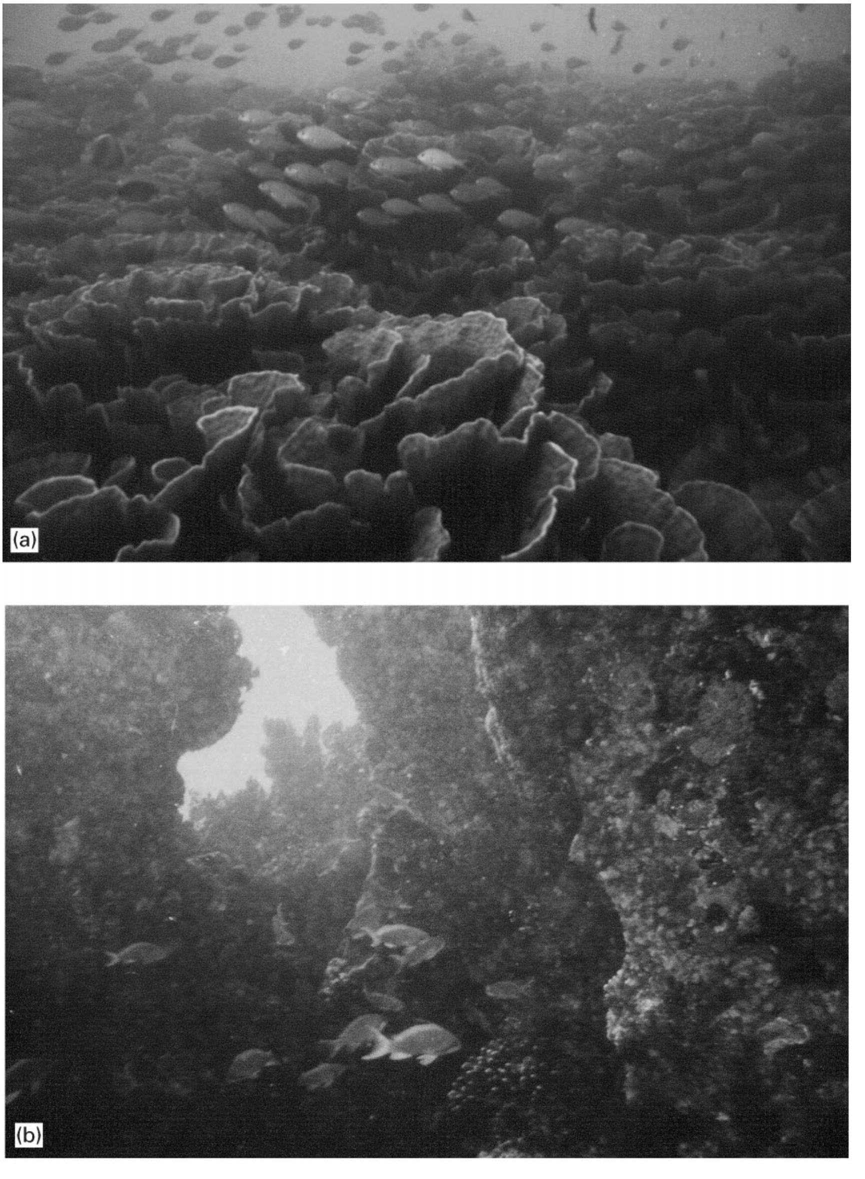


Fig. 2. (a) and (b) Coral reefs are the most diverse marine ecosystems. A single reef in the Indian Ocean might support up to 400 species of fish and more than 100 species of hard coral.

3. Major threats to coral reefs

Generally, the major threats to coral reefs can be divided into two broad categories, those of anthropogenic origin and those that can be considered natural.

However, sometimes the distinction between the two is ambiguous. For example, some threats that are considered natural, such as coral bleaching caused by increased sea temperatures, are intimately linked to increasing global temperatures brought about by man's activities and therefore have an anthropogenic component [3,19].

3.1. Threats of anthropogenic origin

The major anthropogenic threats to coral reefs are intimately linked to high human population densities in coastal areas [6]. Recently, Bryant et al. [18] developed a risk index based on the effect of the greatest threats to the health of coral reef systems namely, coastal development, overexploitation, inland and marine pollution and erosion. This analysis determined that 58% of the world's coral reefs are at medium-to high-level risk of degradation from these anthropogenic disturbances and that greater than two-thirds of those reefs that lie outside the Pacific Ocean are threatened.

3.2. Coastal development

According to Bryant et al. [18], 30% of the world's reefs are at risk from coastal development. The limited space in coastal areas means that development often occurs at the expense of coastal habitats, namely coral reefs. The construction of airports, especially in some small island nations, often occurs directly on coral reef habitats causing direct and irreparable damage to the reef. The use of land fill to provide sites for housing, industry, recreational facilities and other public works threatens reefs through increased turbidity and sedimentation resulting from soil being washed from development sites and onto nearby reefs, particularly during severe rain storms [43,44]. Once the sediment reaches the reef it blocks the sunlight required by the symbiotic zooxanthellae that reside within the tissues of the coral for photosynthesis subsequently affecting the growth of the coral. In severe cases, sedimentation can kill corals outright by smothering them [43]. Often, the dredging of harbours and channels results in similar outcomes. Furthermore, construction within coastal zones often causes an increase in beach erosion as a result of altered water circulation patterns [45].

The construction of hotels and accommodation facilities along the foreshore adjacent to coral reefs increases the number of people living in these areas and subsequently the amount of waste (Fig. 3). Often waste produced by these developments is discharged directly into inshore lagoons without any treatment. As a consequence, reefs situated close to these tourist developments often suffer from eutrophication that promotes increased growth of algae and exclusion of corals [9]. In addition, uncontrolled construction on the foreshore, the construction of up-stream dams and mining of sand in river beds, stops the natural deposition of sand that has accumulated in the dunes onto the beach which inevitably leads to increased beach erosion [46]. In the worst cases entire resorts have simply fallen into the sea.

Coastal development, especially in small island nations where terrestrial resources are scarce, has promoted the practise of coral mining [23,47,48]. The removal of coral for the purposes of cement manufacture destroys the reef and therefore the barrier that protects coastal zones from oceanic waves and storms [9,23]. Removing large quantities of coral also changes the topography of the reef flat and, as a result, alters the patterns of water flow resulting in increased beach erosion [45]. Furthermore, to produce lime ($Ca(OH_2)$) from coral ($CaCO_3$) the skeletons must be burnt (Fig. 4) which indirectly promotes the cutting of mangroves and forest timber for firewood. The estimated cost of such logging is approximately \$7000 USD/km^2 of reef flat that is mined [45].

Fig. 3. A consequence of unplanned urban expansion in coastal zones is the accumulation of waste. Often it is mangrove communities adjacent to population centres, such as this one in Mombasa, Kenya, that bear the brunt of such human ignorance.

Fig. 4. Coral skeletons mined from nearshore reefs are burnt in kilns such as this one in Sri Lanka to produce lime for cement and building materials.

3.3. Overexploitation and use of destructive fishing techniques

Bryant et al. [18] estimated that 36% of the world's reefs were at risk from overexploitation. Fishing is the most widespread activity undertaken by humans that exploits coral reefs [11]. Overfishing using destructive methods such as dynamite, cyanide, muro-ami and kayakas techniques is usually a result of increasing human populations, poverty and declining fish stocks [12] and contributes significantly to the degradation of the world's coral reefs [9,11,13,20,49].

Blast fishing uses explosive charges dropped into the water to concuss and kill fish that are then simply picked up by fishers. This form of fishing is widespread, especially in south-east Asia [45,49,50] and along the east coast of Africa [6,13]. Fishers that use this destructive method usually live in urban areas and lack traditional ties to the areas where they use the explosives or they are desperate to meet immediate requirements for food or income [11]. This method of fishing is highly destructive. A blast at close range shatters the skeletons of all corals destroying the complex substrate that attracts many of the fish in the first place [11,12,45] and at increasing distances from the blast all fish and invertebrates are killed irrespective of whether they are desirable. Intensive blast fishing on any reef can rapidly reduce a once flourishing ecosystem to a pile of rubble [11]. Recovery from this form of destruction would take many years. Subsequently, because the abundance of fish on reef communities is determined by such factors as the complexity of the habitat, coral cover and reef size [51–53], blast fishing can cause a considerable reduction in the fisheries productivity of reefs [11].

Cyanide fishing began in the 1960s in the Philippines as a result of the increasing market for aquarium fish (Fig. 5). Sodium cyanide is used to stun fish so they can be captured easily and exported live to European and North American markets [18]. Since then, 1 million kg of sodium cyanide have been squirted or dumped onto the reefs of the Philippines alone [18]. Unfortunately, this practise has spread both geographically and in the range of species targeted. Cyanide fishing, despite being illegal, is prevalent throughout the southeast Asian region and, in addition to aquarium fish, now targets larger predatory fish such as groupers (Serranidae) and famed Napoleon Wrasse (*Chelinus undulatus*) for the live fish restaurant trade [18,45]. Indonesia is currently the largest exporter of live fish supplying approximately 50% of the world market which is worth approximately $200 million USD per year [45]. Species such as *C. undulatus*, when exported alive to restaurants in Hong Kong and other Asian cities that support sizeable Chinese populations, can fetch prices between $60 and $180 USD per kg [45]. Cyanide fishing, despite being more selective than other destructive fishing techniques, is unsustainable. Cesar et al. [45] predicts that if fish continue to be caught at the current rate the live fish restaurant trade will collapse within 4 yr and the economic loss will approach $46 million USD.

Cyanide fishing is more insidious than other fishing techniques because the more remote reefs that generally escape land-based threats such as pollution, sedimentation and coastal development are the reefs that are prime targets for this method of fishing [18]. Cyanide fishing also damages the corals themselves. At high

Fig. 5. The global trade in coral reef organisms poses a threat to sustainability of reef resources. The capture of fish such as this juvenile *Pomacanthus semicirculatus* for the aquarium trade often means that reefs become denuded of particular species which, in turn, may upset the balance of the ecosystem.

concentrations cyanide kills corals outright [54] and at lower concentrations it impedes the photosynthetic function of the symbiotic zooxanthellae and causes bleaching in corals [55] which, in turn, slows the growth of the coral and renders it more vulnerable to other disturbances [7].

Muro-ami and kayakas drive netting techniques may involve as many as 300 people each using either a weighted scare line or a thrashing palm frond to scare fish into a pre-set bag net. The manner in which the scare lines, each weighted with a stone or length of chain of between 3 and 6 kg, are picked up and dropped onto the reef substrate causes considerable damage to the corals [11,12]. Further, the great number of people involved in these forms of fishing increases the likelihood of physical damage being done to the coral substrate. Finally, when the nets are retrieved they are often fouled on colonies of coral, especially branching Acroporids, which invariably leads to breakage of these branches and further damage to these colonies [11] (Fig. 6). These forms of fishing are non-selective and result in considerable by-catch of undesirable species.

Overfishing causes a change in the size distribution of fish populations, decreases in abundance and shifts in species composition [10], genetic structure and life-history characteristics of some target species [11]. Furthermore, overfishing can lead to the removal of keystone predators which may cause shifts in the community dynamic of a reef [11–13,19]. For example, on Kenyan reefs overfishing of triggerfish (Balistidae) resulted in a dramatic increase in the numbers of the boring sea urchin *Echinometra matthei* which, in turn, lead to increased rates of reef erosion [56]. Also, on some

Fig. 6. Seine nets dragged across the reef flat by fishers break coral colonies and, as a consequence, can cause significant damage to reefs.

reefs of the Caribbean overfishing of herbivorous fish species reduced competition for algae for the sea urchin *Diadema antillarum* that resulted in a dramatic increase in their abundance. However, afterwards the sea urchins succumbed to a disease that effectively reduced their population size and removed all predator control of algal populations on these reefs. Without continual cropping by herbivores, the algae then began to outcompete the corals by smothering adult colonies and preventing settlement of new recruits. The subsequent reduction in coral cover and structural integrity of the reef reduced the capacity of the reef to withstand physical perturbations. The occurrence of Hurricane Allen then destroyed many of these reefs leaving nothing but piles of coral rubble from which many have never recovered [57,58].

Fish species are not the only examples of overexploitation. Many mollusc species, especially of the genus *Tridacna* (giant clams), have been fished to extinction in some parts of the Philippines. Sea urchins (Echinoidea) and sea cucumbers (Holothuroidea) have apparently vanished from certain reefs in the Galapagos [18].

3.4. Land-based pollution

Coral reefs have flourished in waters with extremely low nutrient levels through efficiently recycling nutrients within the system [3,5]. The addition of nutrients as untreated effluents from coastal population centres has caused dramatic changes on some reefs within these areas [13,47,50]. The addition of nutrients promotes the growth of algal competitors which may smother the corals and inhibit the settlement of new recruits. Increased nutrient loads also cause algal blooms (Fig. 7) that increase the turbidity of the water and block the sunlight necessary for the coral's

Fig. 7. Influx of nutrients into coastal waters promotes the proliferation of algal blooms and other micro-organisms. These so-called *Red Tides*, such as this one seen on the Atlantic coast of Mexico, can produce toxic substances harmful to organisms residing in these shallow coastal waters.

zooxanthellae to photosynthesise. This reduces coral growth and in severe cases can cause death.

Poor agricultural practices and deforestation have also led to decrease in the extent of coral reefs, especially near river mouths [18,19,46]. Deforestation increases the vulnerability of a watershed to erosion and flooding. Subsequently, rainfall washes soil, pesticides and fertilisers from arable land into rivers which are then transported to coastal waters and dumped on nearby coral reefs (Fig. 8). The sediments smother the corals impeding coral growth and in severe cases killing the coral [43]. Destruction of mangrove habitats at the mouths of these rivers may

Fig. 8. Erosion of land though deforestation and poor agricultural practices increases the input of sediment into coastal waters thus smothering corals and blocking the sunlight needed for the zooxanthellae to photosynthesize. Only a few sediment-tolerant species can survive in this environment and as a consequence the distribution of corals near river mouths is decreasing.

exacerbate the problem as they act as filters removing excess sediment and nutrients from the water [9]. If they have been removed to create space for aquaculture, coastal development or simply to supply firewood (Fig. 9) then the sediment and nutrients are not retained and are washed directly onto the reefs.

3.5. Threats of natural origin

3.5.1. Bleaching of coral and the significance of increases in global sea temperature

In order to understand the phenomenon of bleaching, something of the relationship between the coral and its symbiotic dinoflagellate zooxanthellae must be known. The existence of corals and coral reefs is dependent on a mutualistic symbiotic relationship between the individual coral polyp and a photosynthetic dinoflagellate known as zooxanthellae. Until recently, zooxanthellae were thought to belong to a single pandemic species, *Symbiodinium microadriaticum*. However, it is now known that zooxanthellae are in fact a very diverse group comprising many species [59–61]. The zooxanthellae are intracellular residents of the tissues of the coral [59] and provide the coral with energy (sugars and amino acids) produced by its photosynthetic activities [59,62–64]. In return, the coral effectively fertilises the zooxanthellae providing nutrients in the form of ammonia and phosphates which are waste products of the coral's metabolism [59]. Symbioses between a primary producer and a consumer such as this are paramount to the survival of coral reefs because they ensure that nutrients are recycled within coral reef systems and are not lost to the surrounding oligotrophic waters [3,5].

Bleaching of hard corals and several other benthic invertebrates that possess zooxanthellae, such as soft corals (Alcyonaria), anemones (Actiniaria) sponges

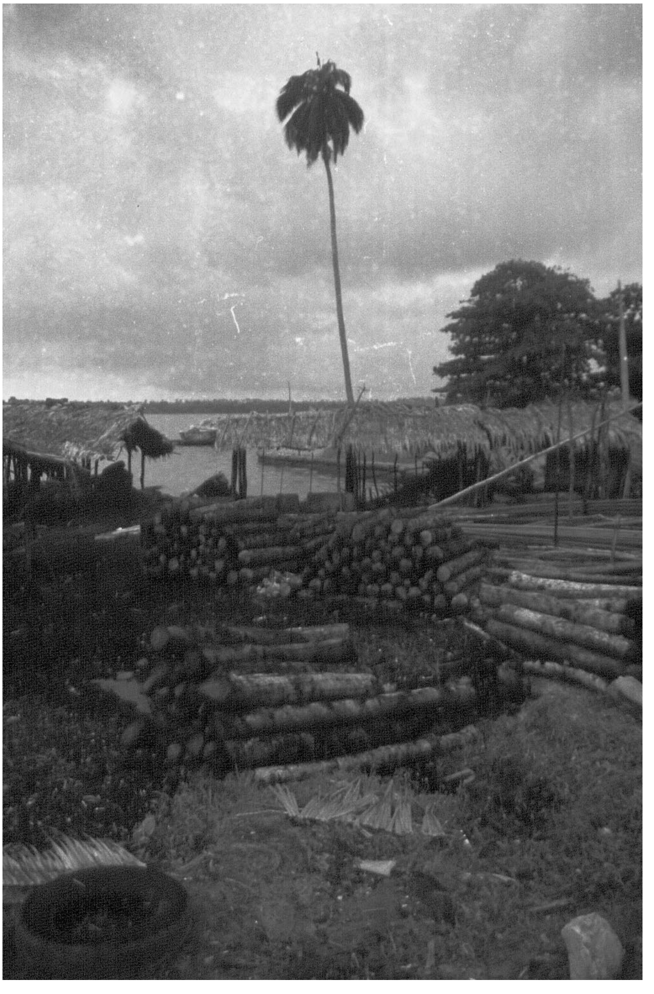


Fig. 9. Mangrove ecosystems formed in the coastal waters protected by coral reefs are an important refuge and nursery for juvenile fish, many of which migrate to coral reefs as adults. Unfortunately, mangroves are an easily accessible source of firewood and the clearing of these ecosystems poses a serious threat to coastal communities.

(Porifera) and clams (Tridacnidae) is a sign of stress [7,65,66] and can result either from the loss of zooxanthellae [67,68] or from loss of zooxanthellar pigment [69] or both [66,70,71]. A variety of adverse environmental conditions, such as reduced salinity [67,72,73], fluctuations in light intensity [67,68,74–76], increases in sea temperature [3,7,65,67,75,77–80], bacterial infection [81] and contamination from chemicals such as cyanide introduced during cyanide fishing [54,55] and pesticides [3], have all been implicated in causing bleaching in reef-building corals. However, increased sea temperature is undoubtedly the primary cause of mass bleaching of coral. Several authors have reported that elevated sea temperatures reduces the photosynthetic rate of the zooxanthellae [67,82–85]. Initially, this was thought to be caused by a malfunction of the light photosynthetic reactions. Recently, however, Jones et al. [76] have demonstrated that it is in fact the dark photosynthetic reactions that are affected by increased sea temperatures and also that increased light intensity plays a significant secondary role. Under normal circumstances the rate of photosynthesis of the zooxanthellae increases with increasing amounts of light until the threshold or saturation point at which photosynthesis can no longer utilize the available light energy [3]. When the amount of available light surpasses this threshold the excess energy is dissipated through non-photochemical pathways. However, when corals and their zooxanthellae are exposed to increased sea temperatures Jones et al. [76] reported that a malfunction of the dark photosynthetic reactions occurs preventing the zooxanthellae from dissipating excess photosynthetic energy. As a consequence, over-reduction of light reactions occurs producing toxic singlet oxygen, super oxide and oxygen-free radicals that cause damage to membranes and proteins. Subsequently, during periods of high sea temperature and high light intensity, such as those seen in the Indian Ocean during 1998, the production of such toxins creates a potentially lethal environment for the zooxanthellae and their host. Thus, in order to prevent intoxication the zooxanthellae are expelled. Once the zooxanthellae are lost from the tissues of the coral, the tissues become transparent revealing the coral's calcium carbonate skeleton giving the coral a white "bleached" appearance (Fig. 10). Although a coral that is bleached retains its own tissues and may survive in this condition for weeks even months, the sugars and amino acids produced by the zooxanthellae are essential for its survival. Therefore, if the conditions that caused the bleaching do not abate allowing the coral to recruit new zooxanthellae it will die [7,66].

Fig. 10. Bleached corals from St. Pierre, the Fahquar Group, Seychelles. Note that the under side of the colony retains some pigment demonstrating the role of light intensity in causing bleaching. Photo: A. Maslennikov.

Fig. 11. During 1998 vast expanses of coral suffered bleaching as a result of El Niño driven increases in sea temperature. Photo: A. Maslennikov.

During 1998 coral reefs of the world suffered a bleaching event that many regard as the most severe ever witnessed [3,7] (Fig. 11). Reports of coral bleaching that lasted for several weeks or months were obtained from all tropical regions of the globe [4]. The subsequent mortality of corals was extensive. The Indian Ocean, in particular, was seriously affected with morality frequently exceeding 75% and sometimes approaching 90% [7,86]. Further, almost half of all corals on several reefs in the East, Central and West Pacific, and the Caribbean were killed [4].

Similar to previous mass bleaching events, bleaching was most pronounced in shallow water (<15 m) and was most severe on rapidly growing species such as *Acropora, Montipora* and *Echinopora*. Most alarming however, was that unlike past bleaching events in which massive corals such as *Porites* survived, the mass bleaching of 1998 affected virtually all species of coral and was recorded at unprecedented depths (down to 42 and 50 m in Sri Lanka and Maldives, respectively) [4,87]. The severity of the 1998 bleaching event was further exemplified by the death of corals that had survived for the past 700 yr or more [3,7,88].

Prior to 1979 bleaching of coral was known only as a local phenomenon. Since then six mass bleaching events have occurred, each coinciding with a period of El Niño [3]. What then has caused the increase in number of mass bleaching events and what is the significance of El Niño? The last two decades has been the warmest period ever recorded during which 1998 was the hottest single year [7]. Subsequently, the temperature of the sea is rising at rates greater than ever recorded. In the last 100 yr the mean global sea temperature has increased by 1°C and the latest predictions suggest it will rise by approximately 2°C within the next 50 yr [89]. This has brought sea temperatures close to the upper thermal limit of many corals and their zooxanthellae. As a consequence, any thermal anomaly that causes abnormal rises in the sea temperature is sufficient to cause bleaching.

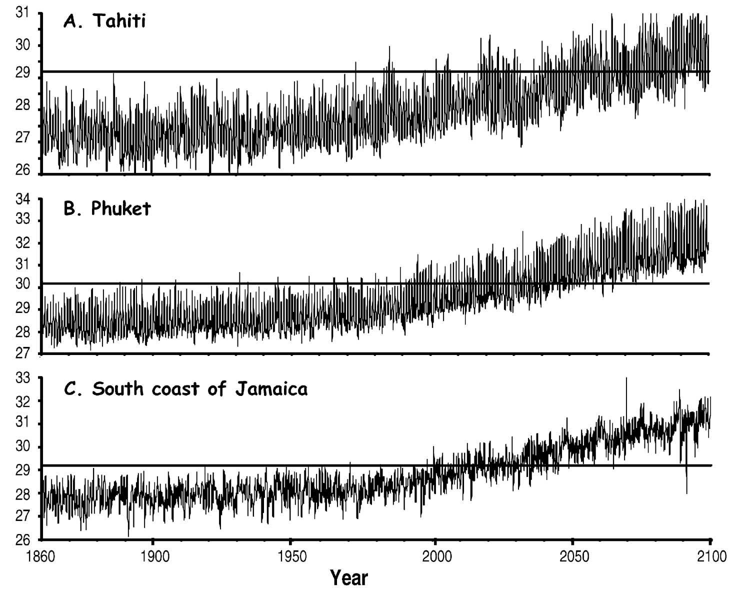
If increases in sea temperature are the cause of mass bleaching events, why then do they coincide with periods of El Niño? Periods of El Niño are the trigger that cause mass bleaching events and the El Niño of 1997–1998 was the most extreme ever recorded [7]. El Niño is a climatic state during which low air pressure systems in the tropical Pacific Ocean migrate from their usual location over the Australian/Indonesian region to the central tropical Pacific (Tahiti). As a consequence, the normal easterly trade winds become weaker producing relatively calm weather conditions near the equator. Subsequently, solar radiation that would otherwise be dissipated by surface winds, currents and mixing of oceanic waters is absorbed causing the sea temperature to rise. If these conditions prevail, then the sea temperature will increase to such an extent that it exceeds that which can be tolerated by the corals and their zooxanthellae, leading inevitably to bleaching. Once bleached, the likelihood that a coral will die is proportional to the length of time for which the thermal limit of the coral is exceeded [3,75].

In late 1997, and continuing through much of 1998, surface sea-water temperatures rose progressively throughout the world. Over much of the tropical oceans where corals are found, sea-surface temperatures increased 2–3°C and in large areas as much as 4–6°C. Direct measurements by divers and the use of sensors showed that the temperatures in places such as Sri Lanka were clearly elevated down to 40–50 m [4]. The bleaching of coral resulting from these temperature increases was the worst ever witnessed [3,7].

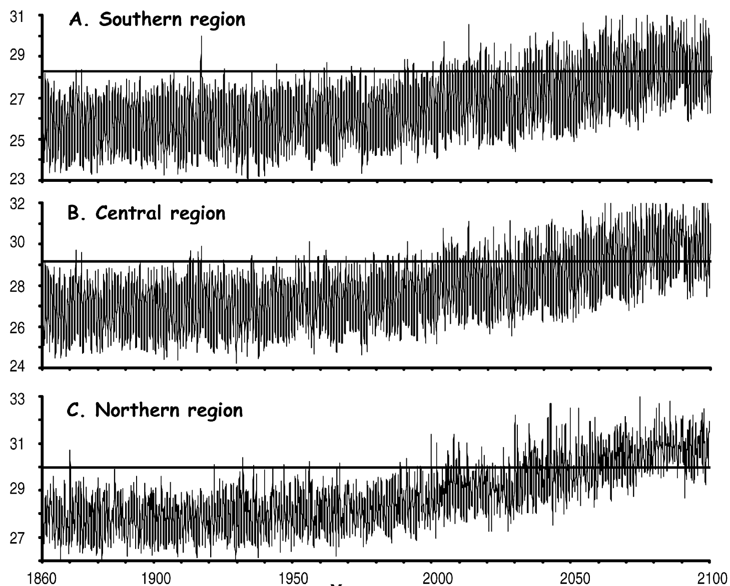
At present, mass bleaching of corals only occurs if a period of El Niño of sufficient strength prevails for long enough to cause significant increases in sea temperature. However, if global sea temperatures continue to rise as is predicted, becoming closer to the thermal tolerance limit of corals, El Niños of smaller magnitude will be sufficient to cause bleaching. Moreover, the closer the mean sea temperature is to the thermal limit of corals the longer will be the period for which the tolerances of corals will be exceeded during any El Niño, thus increasing the likelihood of coral mortality. Eventually, the mean sea temperature will reach a level where normal seasonal increases in temperature during summer will be sufficient to cause mass bleaching of corals [3,7]. Unless changes to current predictions of rising sea temperatures occur, Hoegh-Guldberg [3] forecasts that annual bleaching of corals will begin in southeast Asia and the Caribbean around the year 2020 (Fig. 12a), in the northern GBR approximately 2040 and in about 2070 on the southern GBR (Fig. 12b).

3.5.2. The consequences of mass bleaching

Reduced reproductive capacity and recruitment. Increased frequency and intensity of bleaching will obviously lead to greater mortality in mature colonies of coral. In colonies that survive, bleaching is likely to inhibit reproduction through the reduction in fecundity and reproductive output thus limiting the chances of successful fertilisation and settlement [3,7]. However, if some corals do manage to settle, several years are required before they become reproductively mature. If the



(a)



(b)

Fig. 12. The predicted increases in sea temperature over the next century at three sites in the northern hemisphere (a) and along the extent of Australia's Great Barrier Reef (b) derived from the ECHAM4/OPYC3 IS2a climate model. The solid horizontal line represents the known thermal tolerance limits of corals at each particular site. If sea temperatures continue to rise as is predicted by this climate model then bleaching of corals will very soon become a annual phenomenon. If the subsequent mortality of corals as a result of this annual bleaching is comparable to that recorded during the 1998 event then the continued existence of corals and the health of the world's coral reefs could be seriously jeopardized. Source: Hoegh-Guldberg (1999).

frequency of mass coral bleaching and mortality exceeds that which is required for the attainment of reproductive age then perpetuation of the species will be hindered.

Reduced rate of calcification and growth. The products of photosynthesis by zooxanthellae are the primary source of energy used by corals for calcification and skeletal growth [63]. Therefore, the loss of zooxanthellae because of bleaching reduces the amount of energy available for accretion of calcium carbonate and subsequently growth. For the corals themselves, reduced growth rates might translate into reduced competitive capacity and loss of space to algal competitors, ability to recover from disturbance [3,7], susceptibility to disease and attack from bio-eroding organisms and an inability to remove sediment [7]. For the entire reef, on the other hand, reduced rates of calcification and growth of corals might significantly compromise the structural integrity of the reef.

Exacerbating the effects of bleaching on the rate of calcification are increasing levels of carbon-dioxide (CO_2) in the atmosphere. As the concentration of atmospheric CO_2 increases, so too will the acidity of the sea water which will cause a concomitant decrease in the available carbonate [1,3]. At the present rates of CO_2 increase Hoegh-Guldberg [3] predicts that the rate of calcification of corals will decrease by between 14 and 30% by the year 2050 and a net loss of calcium from the system through physical- and bio-erosion will further weaken the framework of the reef. Once the structural integrity of the reefs are compromised the reef itself can be rapidly eroded resulting in the destruction of coastlines, loss of housing, tourism and coastal ecosystems such as mangroves and sea grass beds upon which many commercially important species rely for reproduction and nursery areas [1].

A mechanism for change in community composition. Some species of corals are more tolerant to fluctuations in temperature than others. For example, during previous bleaching events it was the Acroporid corals, especially the branching and tabulate forms that were most susceptible. Large massive forms such as *Porites* spp. seemed less affected and when some colonies did lose their zooxanthellae they were among the first to recover. This differential ability of corals to cope with temperature change could lead to changes in community composition toward more heat-tolerant species. Goreau and Hayes [80] suggested that coral species present on reefs at higher latitudes might be replaced by more temperature tolerant species from lower latitudes. This may occur in the short-term but if sea temperatures continue to rise then the thermal tolerances of all corals will be exceeded and they will be replaced by more heat-tolerant species. Obviously, the consequences of shifts away from coral communities will have an effect on associated fauna and flora. The most important of these to human populations will be the decline in fish stocks upon which many millions of people depend.

3.5.3. Tropical storms, volcanic and tectonic activity

Coral reefs are also subjected sporadically to tropical storms, encroaching lava flows or upheaval of land associated with volcanic or tectonic activity [19,90]. While these unpredictable forces of Nature can cause massive damage to reefs, the damage tends to be localised, seriously affecting only a few reefs within a small area. The real threat is when these natural perturbations affect reefs that are already disturbed by human influences. In such cases recovery of the reef ecosystem may be severely retarded or might not happen at all [58].

3.5.4. Outbreaks of Crown-of-thorns starfish

Population outbreaks of the Crown-of-thorns-starfish *Acanthaster planci* have been recorded throughout the world since the early 1960s (see reviews by Endean [91], Potts [92], Moran [93] and Birkeland and Lucas [94]). The damage done to reefs by feeding aggregations of this corallivorous starfish is devastating and reports of up to 90% of the live hard coral cover of reefs being consumed are common [95–98]. The question as to what causes population outbreaks of *A. planci* on some reefs is one of the most asked in modern marine science. Despite the plethora of hypotheses attempting to explain this phenomenon (see review by Moran [93]), to date, a satisfactory answer has not been forthcoming. Regardless of the cause(s), outbreaks of this starfish appear to be occurring more often and in some areas pose a serious threat to continued health of coral reefs.

4. Socio-economic impacts of coral reef degradation

The socio-economic consequences of the bleaching event are obvious but difficult to quantify. Only speculative estimates are available and have been provided by several authors. Cesar et al. [45] estimated that the cost resulting from destructive fishing methods on Indonesian reefs resided somewhere between $137 000 USD and $1.2 million USD/km^2 of reef over a 25-yr period. Wilkinson et al. [7] and Cesar [22] estimate that the economic cost of the 1998 mass bleaching event might range anywhere from $700 million USD to in excess of $8 billion USD over the next 20 yr. The bulk of these losses are a result of decline in fisheries (between $260 million USD and $1.3 billion USD), tourism (between $332 million USD and $3.4 billion USD) and coastal protection (up to $2.1 billion USD depending on the extent of reef framework collapse). However, these authors acknowledge that the effect on human populations will extend far beyond the scope of economics. The loss of livelihoods and food security for the millions of people that depend on coral reefs is impossible to value. At present, Coral Reef Degradation in the Indian Ocean (CORDIO), a multi-disciplinary research programme involving scientists from 12 countries, is being implemented to determine the biological and socio-economic effects of the 1998 mass bleaching event on the entire Indian Ocean region (see Box 1 for details). Preliminary results from initial investigations indicate that economic losses from tourism and fisheries will be significant [99].

Box 1

Assessment of the damage — the CORDIO programme

CORDIO was started in January 1999. The programme has as its goal to provide information on the extent and speed of coral degradation in the Indian Ocean. At present the programme supports about 25 targeted studies and monitoring projects in 12 countries. Ecological as well as socio-economic effects are studied. Investigations also focus on the natural recovery processes on different reefs, and methods of mitigation of damage and artificial recovery of reefs. In addition, the programme intends to support alternative livelihoods among local human populations affected by the coral mortality. During its first year the programme received about US$ 1 million from the World Bank (through the Dutch Trust Fund), Sida (Swedish International Development Cooperation Agency), the Swedish Council for Planning and Coordination of Research, the Foundation for Strategic Environmental Research and WWF-Sweden.

Projects to study the status of the reefs, including the signs of recovery or continued deterioration are carried out in Kenya, Tanzania and Mozambique, as well as throughout the Seychelles and Maldives archipelagos, Mauritius, Reunion, Comores, Sri Lanka and the Indian reefs in Bay of Bengal (Andaman and Nicobar) and in Gulf of Mannar and the western Indian Ocean (Lakshadweep). These studies have not provided enough compiled data yet and it is too early to report any results. However, it is obvious that there is a significant recovery in some reefs in East Africa, while in isolated reefs in Maldives, Seychelles and Sri Lanka, no signs of recovery were seen about 1 yr after the peek of the bleaching. Some reefs in East Africa and in Sri Lanka have been transformed into algal-covered reefs. It is difficult to believe that some of these reefs will be able to recover in foreseeable future.

Projects to study the secondary effects on the fish communities and other reef organisms are carried out in a few projects in East Africa, South Asia and the Indian Ocean Islands. A preliminary account of these results show that the fish communities associated with the coral reefs were affected, and algal feeding fish tended to increase in numbers while coral feeding species decreased. In some areas the entire reef fish communities (abundance and diversity) decreased to less than 25% of their former levels. Some studies reported drastic reductions in butterfly fish numbers. Monitoring of the potentially toxic, epiphytic dinoflagellates has shown drastically increased concentrations in areas with dead corals.

Studies to investigate the socio-economic impacts of the bleaching in coastal communities in affected areas have only just started, and therefore it is too early to report any results. Also studies to look into the effects on tourism, particularly the dive tourism, has also only just started.

The implementation of the projects under the CORDIO programme is coordinated from three centres in the Indian Ocean Region. The actual project, including field sampling and compilation of results, is carried out by about 10 country teams.

5. Recovery of coral reefs from disturbance

5.1. Natural recovery

Coral reefs are fairly resilient ecosystems [4]. Nevertheless, with man's activities becoming more extensive and more exploitive this inherent resilience is being threatened. How a coral reef will recover from a disturbance and the length of time required is difficult to predict. Obviously, how quickly a reef will recover will depend on the nature and magnitude of the perturbation and also the community structure and composition of the reef. However, several factors can be identified as important for the natural recovery of a reef:

- *Cessation or alleviation of the perturbation causing the degradation* — Obviously, if the disturbance causing the degradation of a reef is still active then there is little chance of recovery.
- *The presence of other disturbances (e.g. pollution, sedimentation, removal of keystone species)* — If coral reefs are suffering under the influence of anthropogenic disturbances then their recovery will be hindered. For example, an influx of nutrients in the form of untreated sewage might cause an algal bloom that stops light from reaching the coral. Without light the growth of the coral is retarded which, in turn, compromises the ability of the coral to overcome disturbance and compete with other benthic organisms. If the nutrient influx persists, then the growth of benthic macro-algae might increase allowing them to overgrow and smother the coral leading to a change in community composition.
- *The influx of coral larvae from other reefs* — The recovery and regeneration of disturbed areas of reef is dependent on the influx of coral larvae that settle and grow. The number of larvae a disturbed reef will receive will depend on its juxtaposition with other undisturbed reefs. If, for example, the reef is an isolated reef, then larval input might be limited which, in turn, will cause slow rates of larval settlement and longer periods of recovery [7]. On the other hand, if the reef is part of a group of reefs, such as one situated within the Great Barrier Reef, then recovery is not likely to be limited by recruitment but will be determined by other factors such as the magnitude and extent of the disturbance.
- *The extent of the disturbance* — If the disturbance is only local then there is a greater likelihood of larval input from surrounding reefs and also untouched portions of the damaged reef [7] and, as a consequence, relatively rapid recovery. If, on the other hand, the damage is regional then other factors such as larval dispersal, the length of time larvae remain competent to settle and patterns of local extinction become important determinants of how long before a reef recovers to its pre-disturbed state.
- *The timing of the disturbance* — Most corals reproduce sexually only once per year when the temperature of the water is near its maximum. Therefore, an influx of larvae into the system also occurs only once per year. If the disturbance occurs soon after this reproductive period then it will be almost 1 yr before potential new recruits have an opportunity to settle. This might allow other benthic species that

reproduce more continuously to settle and occupy the substrate thus limiting future settlement of corals. Furthermore, a disturbance during this reproductive period might cause the failure of any corals to settle that year further impeding recovery.

- *The species composition of the community* — Provided the condition of the substrate permits, fast-growing corals will rapidly expand into space created by a disturbance. Therefore, a community with a greater percentage of fast-growing corals might be expected to recover from disturbance quicker than one dominated by slow-growing, persistent species.
- *Local extinction of particular coral species* — In such an event the re-establishment of the extinct species on a disturbed reef will dependent entirely on influx of larvae from extraneous sources. If this does not occur there will be a change in community structure and recovery might proceed to an alternative stable state.
- *Survivals of some polyps on the colony* — When corals bleach, often only polyps on the upper surfaces of the colony expel their zooxanthellae. This is a consequence of the significant role played by high light intensities in contributing to bleaching (see above) and the differences in the amount of light absorbed by polyps on the upper and lower surfaces of the colony. If polyps situated on the shaded, underside of the colony survive they can regenerate and grow over the damaged portion of the colony and assist recovery.
- *Survival of adult corals in deeper water* — Colonies of coral in deeper water are often not exposed to the increased temperatures and high light intensities necessary to cause bleaching. The survival of these colonies can assist recovery by contributing larvae for settlement and regeneration of damaged areas of reef.

5.2. Assisted recovery

During the past decade artificial rehabilitation of degraded reefs has received considerable attention [48,100,101]. Unfortunately, artificial rehabilitation of coral reefs is a very expensive exercise [48] and Lindahl [101] points out that the expense involved is beyond the financial capacity of many countries in which coral reefs occur. However, if artificial rehabilitation is contemplated several factors must be taken into account. First, is the perturbation that caused the degradation still active? Obviously, if it is then rehabilitation will be a fruitless exercise. Second, it is imperative to determine the likelihood that a reef will recover by itself. If it is, then the reef is probably best left to its own regenerative devices. Conversely, if the reef is unlikely to recover without intervention then definite goals should be outlined before rehabilitation commences. For instance, do you want to stabilise the substrate to allow corals to settle naturally? Do you want to rapidly increase the cover of coral? Do you want to develop a community similar in structure and species composition to an undisturbed community? The goals you define before you start will determine the methods you adopt and the expense incurred. Ultimately, however, if artificial rehabilitation of degraded reefs is going to be a viable option in tropical developing countries a cost-effective method must be devised that can be implemented using a minimum of specialised equipment [101]. See further discussion of this issue in the article by Yap herein.

6. Recommendations and future perspectives

6.1. Implementation of integrated coastal zone management

With the exception of direct overexploitation of reef resources, most anthropogenic threats to the future health of coral reefs originate on land. Subsequently, if sustainable use of reef resources is to be achieved management strategies must also incorporate land-based activities so that potential threats such as sedimentation resulting from deforestation, coastal development and poor agricultural practices are recognised and dealt with appropriately. During the last decade the concept of integrated coastal zone management (ICZM) has come to prominence [102] offering a muli-faceted approach to management of both marine and terrestrial resources. A comprehensive ICZM plan should consider the wishes of all user groups, such as local people, local and federal governments, commercial organisations, non-governmental organisations, conservation lobby groups and scientists, and promote open dialogue between them. The introduction of ICZM into tropical developing nations provides a mechanism by which anthropogenic disturbances to coral reefs can be mitigated and resources used sustainably [7,12].

6.2. Development of alternative livelihoods

Traditionally, many coastal communities in tropical developing countries have been reliant on coral reefs for food and economic well being through the conduct of artisinal fishing. However, burgeoning coastal populations is increasing the pressure on coral reefs to continue to supply a rich bounty. Faced with ever diminishing resources, the prospect of economic failure and the lack of any alternative source of income, fishers are increasingly turning to destructive fishing practices to maintain catch sizes and profitability. The alleviation of this sole dependence on coral reef resources is the key to achieving sustainable resource use in these regions. Moffat et al. [103] suggests the only way to accomplish this is through community development.

The introduction of alternative livelihoods to people traditionally dependent on coral reefs serves to reduce exploitation of coral reefs in a number of ways. McManus [12] demonstrates that providing an alternative source of income to fishers reduces the fishing pressure on the reef by making fishing less profitable. This is because in order to go fishing the fisher forgoes whatever income they would have gained from their alternative source hence increasing the amount of fish needed to be caught before a profit is returned. Subsequently, when offered a choice some fishers will stop fishing in favour of the alternative livelihood thus alleviating some of the pressure on coral reef resources. Furthermore, once families develop the financial capacity to purchase food and other goods they are no longer dependent on the reef as their sole source of food.

One of the obvious alternative sources of income in coastal areas supporting coral reefs is tourism. Coral reefs are one of the biggest draw cards for tourism and the introduction of tourism to coastal communities provides a mechanism for economic growth and community development. In addition, because tourists are attracted to the natural beauty of coral reefs, the economic gains generated by tourism will provide incentives to preserve the natural features of the reef rather than exploit them. It should be noted, however, that, despite the benefits of tourism, its introduction into coastal areas often brings undesirable factors such as unplanned coastal development which leads to erosion of beaches and eutrophication of coastal waters. The introduction of tourism to coastal communities of developing nations should therefore be planned and closely managed by all interested parties.

Another example of an alternative livelihood is aquaculture exemplified by the sea weed farming undertaken on Zanzibar, Tanzania. The cultivation of sea weed (*Eucheuma spinosum*) was introduced in the late 1980s to traditional fishing villages situated inshore of the fringing reef on the east coast of Zanzibar [104]. Sea weed, grown in the sheltered lagoon behind this fringing reef, is now one of the largest export earners of Zanzibar. This industry provides an alternative to fishing and an additional source of income for families residing in these coastal communities. Furthermore, because sea weed farming is conducted by the women of the villages, they derive this financial benefit independent of the men which has given them a degree of independence and has also brought greater financial security to individual families within these communities.

6.3. Capacity development

One of the keys to ensuring the sustainable use of resources is having the ability to gather appropriate information to make the correct management decisions and then having the capacity to implement those decisions. Unfortunately, many of the nations that are charged with ensuring the future health of the world's coral reefs do not possess sufficient capacity in either of these sectors. Subsequently, increasing the capacity of scientists and managers to gather pertinent information describing the status of coral reef resources should be one of the primary objectives of any national programme. The international community can assist with training courses and exchange programmes between developed and developing nations. Several organisations such as the Global Coral Reef Monitoring Network (GCRMN) and CORDIO are, at present, conducting such courses ensuring that the nations that possess coral reefs have the capacity to monitor their reefs and identify future trends in their health. In addition, assistance should be given to scientific development, especially in tropical developing nations. Scientists in these regions should have the capacity to recognise and prevent problems arising in their own countries and they should have significant input on management decisions.

The second facet of capacity development is concerned with implementing and enforcing management decisions. Often nations in which coral reefs occur have neither the human nor financial resources to do so. The low salaries of managers and poor job security of government officials make these people vulnerable to bribery and political intimidation which further exacerbates the problem [19]. Obviously, financial donations can be made by the international community but this is often only an immediate solution. A long-term solution is to promote a system of self-regulation in which local user groups monitor and manage activities conducted on reefs. To achieve this form of management it must be demonstrated to local user groups why there is a need for management and what the consequences of unregulated exploitation are. For this to succeed it is imperative that local user groups are involved from the outset in the development and implementation of management strategies. The development of such self-regulatory processes negates the need for otherwise expensive government enforcement and circumvents problems associated with corruption.

6.4. Appropriately managed marine protected areas (MPAs)

The Fourth World Congress on National Parks and Protected Areas called for a minimum of 10% of each of the world's biomes to be incorporated into protected areas. The current number of protected areas in marine environments is well below this recommendation [105]. Jameson et al. [9] suggested the current number of marine protected areas and their dispersed nature are inadequate to preserve the biodiversity and fisheries stocks on coral reefs in any part of the world except in Australia's Great Barrier Reef Marine Park. These authors recommended that a worldwide system of marine protected areas that includes widely dispersed small reserves and several strategically located large reserves encompassing 20% of the world's coral reefs should be set up.

While there is increasing evidence that marine parks contribute to the diversity of adjacent areas through the export of larvae and emigration of adults and protection of spawning stock [19,106,107], institutionalising marine parks must be done in the appropriate places for the appropriate reasons and in the appropriate manner. Kelleher et al. [105], following the guidelines set out by Kelleher and Kenchington [108], provide a comprehensive account of "where" and "why" marine parks should be set up but in developing nations it is often the "how" that is the most difficult to accomplish successfully. Marine parks in these regions often fail because there is lack of public support and willingness of users to follow rules, poor enforcement either through lack of commitment or lack of financial and technical resources, or through failure to address impacts that originate outside the bounds of the marine park [105,109]. Further, in these countries traditional marine parks that conserve resources through strict regulation of access cannot work because of the dependence of these communities on these resources for their economic and physical well being. You cannot ask users to make sacrifices for conservation without providing suitable and viable alternatives. Therefore, biodiversity must be conserved through sustainable use of resources and effective management and the only way to achieve this is to focus on the local people most affected by the implementation of the marine park. To ensure the success of marine parks in these regions user groups must be incorporated into every stage of the park's development. If a feeling of ownership of the park is instilled in the people of the community that depend on the park then they will feel like they have an obligation to see that it is successfully managed. Furthermore, McClanahan [109] warns that a MPA has greater chance of success if it is profitable. Indeed, if local communities can see how the setting up of a marine park can benefit them financially through tourism and continued availability of resources they will be more receptive giving the marine park a greater likelihood of success.

6.5. Increase monitoring of coral reefs

The great majority of the world's reefs occur in remote locations and, as a consequence, their condition is unknown [18]. Obviously, without appropriate data describing their condition and trends in their health-making decisions regarding the sustainable use of their resources is difficult. Therefore, increased monitoring of reefs is clearly needed. Wilkinson [4] demonstrates that two products are yielded from regular monitoring of the state of coral reefs. First, the data that describes the status of coral reefs of the world and the establishment of trends in their health and second, the public awareness that is generated by the collection of those data. At present, there are several organisations (GCRMN, Reef Check, Aquanaut, Coral Reef Alliance) conducting monitoring of coral reefs. However, it has only been in the last few years that these organisations have begun to monitor reefs and as yet many reefs remain unsurveyed.

6.6. Tighter controls on fishing practices especially those employing destructive techniques

Broad-scale testing for cyanide residues in exported and imported fish should be implemented. For example, a recent alliance has been formed between the government of the Philippines and the International Marinelife Alliance that has set up a network of laboratories around the Philippines to test exported fish for levels of cyanide in their tissues [18]. Reef Check [88] called for similar testing of imported fish in target cities for the live fish trade such as Hong Kong and suggested that offending exporters and importers should be punished with sentences that would dissuade the use of poisons for capturing live fish. In addition, the sale of fish captured using blast fishing techniques should be prohibited. To facilitate such legislation fisheries managers and fish market agents should be taught to recognise fish captured using blast fishing techniques and should report fisherman engaging in these destructive activities.

6.7. Change the focus of existing fisheries management

Many of the current fisheries management techniques have been developed on temperate single species fisheries where the trophic network is simple and predictions regarding the effect of harvesting on the ecosystem and sustainability of the fishery easier to make. However, in tropical, coral reef ecosystems the trophic network is highly complex involving a great many interdependencies between species, many of which are unknown. As a result application of single-species fisheries management models to coral reef systems is not necessarily wise [110]. In fact, exploitation of a single-species or single ecological group (e.g. herbivorous fish) can lead to dramatic shifts in the community dynamic [56,58]. Therefore, the need for alternative management strategies in coral reef fisheries is urgent. Jennings and Polunin [11] and Russ and Alcala [110] have proposed a method that makes use of the trophic complexity of coral reefs and the moderating effect that it brings. They recommend that harvesting of coral reefs should be done in a multi-species way so that species from each trophic group are taken thus, maintaining the diversity both within and between trophic groups which prevents unwanted shifts in the community dynamic. In addition, the fishery as a whole is less reliant on the success of one particular species and, as a result, is less vulnerable to natural fluctuations in population size. Of course, harvesting species from all trophic groups requires that there be a market for representatives from each group. At present, this method of fisheries management is not being promoted. Current fisheries development programmes persist with targeting a few select species.

7. Conclusions

The majority of the world's coral reefs are situated in the national waters of developing nations. The widespread poverty and overpopulation of the coastal zones of these nations places an unsustainable burden on their reefs such that their future could be seriously jeopardised. Only through the systematic implementation of integrated coastal zone management that involves all user groups and managers alike and focuses on poverty alleviation through community and capacity development and issues of public awareness will sustainable use and conservation of coral reef resources be achieved. Without such action the future health of both human and coral reef populations could be compromised.

Furthermore, the spectre of global warming and rising sea temperatures determines that reef management and conservation is no longer the sole responsibility of countries fortunate enough to have coral reefs. Ensuring the sustainability of the world's environment is now the responsibility of all nations including the industrialised, first-world nations of Europe and North America. The United Nations Environmental Programme (UNEP) uses an African proverb that states "we have not inherited the earth from our parents but rather we have borrowed it from our children". If anthropogenic stresses on coral reefs are not reduced in the near future we seriously risk defaulting on that loan and becoming environmentally bankrupt.

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